CALIFORNIA
ENERGY
COMMISSION

ENERGY INNOVATIONS SMALL GRANT PROGRAM
Building End Use Energy Efficiency

HIGH-EFFICIENCY SINGLE-PHASE AIR CONDITIONER

FEASIBILITY ANALYSIS

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EISG Grant Number:
99-39

LEGAL NOTICE

PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million of which $2 million/year is allocated to the Energy Innovation Small Grant (EISG) Program for grants. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University, which is under contract to the Commission.

The EISG Program conducts four solicitations a year and awards grants up to $75,000 for promising proof-of-concept energy research.

PIER funding efforts are focused on the following six RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent Assessment
- Appendices
  - Appendix A: Final Report (under separate cover)
  - Appendix B: Awardee Rebuttal to Independent Assessment (Awardee option)

For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission's Web site at:
http://www.energy.ca.gov/research/innovations

or contact the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at http://www.energy.ca.gov/research/index.html.

High-Efficiency Single-Phase Air Conditioner

EISG Grant # 99-39

Awardee:	Dr Otto J. M. Smith
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Introduction

Electric power system overloads often occur during hot summer afternoons when many residential air conditioners are operating. The majority of these air conditioners are powered by single-phase electric motors. Out of concern for power reliability on these hot afternoons, power companies bring on-line their least desirable power supplies. These are the most expensive to operate, the most polluting or oldest generators. These actions are taken to minimize the probability of system degradation or a blackout. The cost to the power company and to society to supply these air conditioners at the peak load time is high, and is often higher than the rate that the customer is currently paying. Also, emissions from the older power plants are usually higher than the newer power plants. The less desirable power plants would be dispatched less frequently if higher efficiency air conditioners were widely deployed in the marketplace at reasonable prices.

One solution is to power the air conditioners with the more efficient three phase motors. The constraint is that most residences and perhaps 40% of all rural areas have only single-phase power available, and it is uneconomic to change these distribution and wiring systems. The compressors are well designed, but the low efficiency single-phase motors on the compressor shafts are much less efficient than three phase motors of the same power rating.

This project demonstrated the feasibility of using a control system that can operate high-efficiency three-phase induction motors from single-phase power supplies. These control systems were originally developed for water pumping applications by the researcher in previous, unrelated efforts. These controls are trademarked under the name Enabler™.

The use of such controls on three phase air conditioner motors could reduce the electrical power demanded by residential and small commercial air conditioners by 8 to 10 percent. Air conditioner manufacturers would design all products with three phase motors, adding the control system to those sold to market segments where three phase power is not available.

Objectives

The goal of this project was to determine the feasibility of operating air conditioners with three phase motors efficiently on single-phase power. A test program to measure efficiency was very carefully designed and implemented in order to provide high confidence in the test results. The following project objectives were established:

1.) Design, construct and demonstrate a control system specifically for three-phase air conditioner motors enabling them to run using single-phase power.

2.) Demonstrate that residential size central air conditioning units, running on three-phase motors that have been modified with a control system to operate on single-phase power, will consume 10% less electrical energy than equivalent air conditioning units running on single-phase motors.

Outcomes

1.) Control systems were designed and constructed to operate two different three-phase motors from single-phase power. One motor was designated a Model 48T motor, the other, a Model 42T motor. The control systems were capable of operating the three-phase motors. As expected, motor performance was improved. With the control installed on the Model 48T motor, the winding current unbalance was reduced to only one percent, compared to 7.4% with the three-phase power supply. Also, the single-phase input to the control had a power factor of 90.8% LEADING, compared to 75.2% lagging with the three-phase power.

   With the control installed on the Model 42T motor, the winding current unbalance was reduced to 3.2%, compared to an unexpectedly large 13.8% with the three-phase power supply. Still, the single-phase input to the control had a power factor of 88.3% LEADING, compared to 77% lagging with the three-phase power.

2.) All of the objectives were achieved for the two sizes of compressors that were tested. A 48,000 BTU/hour compressor and a 42,000 BTU/hour compressor were tested at an independent commercial testing facility by the professional staff as directed by Dr. Smith. Many tests were conducted. The average Energy Efficiency Ratio (EER) for each configuration is tabulated below, the efficiency improvement is presented in the last row:

Motor Configuration	**42,000 BTU/hour Unit**	**48,000 BTU/hour Unit**
Three-Phase powered three-phase motor	10.816 BTU/Watt-hour	12.436 BTU/Watt-hour
Single Phase motor	10.864 BTU/Watt-hour	10.691 BTU/Watt-hour
Enabler™ controlled single phase powered 3-phase motor	11.294 BTU/Watt-hour	11.950 BTU/Watt-hour
Improvement in Single Phase Powered Energy Efficiency	**3.958 %**	**11.776%**

Conclusions

The feasibility of operating three-phase motors in air conditioners using single-phase power was demonstrated. The motor performance improvement was consistent with that observed in prior development of the controls on larger motors. Without test results from additional like units, it can not be assumed that the savings of nearly 12 % of the electricity use for the 48,000 BTU/HOUR unit with the control system will be realized on all air conditioners of this size. The 42,000 BTU/HOUR unit demonstrated nearly a 4% energy savings. The test results show that the 42T three-phase motor was significantly below average in efficiency. It was less efficient than the single phase motor. The principal investigator concluded that this resulted from low quality in the area of winding current imbalance and suggested that a motor of average quality of this size would have produced greater efficiency gains. Due to the small sample size and variability in motor quality the

Program Administrator estimates the energy savings from this invention to be in the 8% to 10% range on average, but additional testing will be needed to confirm this conclusion. The impact of the tested technology on unit efficiency was significantly affected by motor quality. That quality remains an unquantified variable. If the two three-phase motors selected in this study are representative of the range in quality of commercially available three-phase motors this would suggest that the motor manufacturing industry has a quality control problem that also needs addressing.

The ultimate commercial success of the Enabler™ technology will depend on the impact this technology will have on the retail cost of new air conditioners. The researcher reported that his direct cost for the control system components (purchased at retail) was $128 per unit. The researcher projected that the equipment manufacturers could reduce the direct cost of the control system circuitry to $64 per unit if mass-produced. Based on the $64 cost estimate, the Project Administrator projects an increase of about $100 in retail price per unit of the large 48T class of air conditioner. The control circuit for the smaller units, utilizing smaller capacitors, would have a lesser retail price impact. To put this into perspective, the Program Administrator prepared a simple payback analysis. Two electric rates, $0.10 and $0.25 per KWH, were used to span a broad range of retail prices. The 48T motor tested uses electricity at the rate of 4 KW. By using the new control circuit, one could reduce demand by 10% or 400 Watts. It follows that the modified air conditioner would save 400 KWH in 1,000 hours and 1,000 KWH after 2,500 hours of operation. A person with an electric rate of $0.10/KWH will have a simple payback in 2,500 hours of operation, while a person with a $0.25/KWH rate will achieve a simple payback in 1,000 hours of operation. Depending on the length of the cooling season, payback could occur in one to two cooling seasons. This supports the conclusion that this innovation offers a near term payback to the ratepayer using this control technology with three phase motors.

The researcher asserts that the direct cost of the control system circuitry could be further reduced if the manufacturers of the three-phase motors made some minor design modifications to the motor wiring. While additional research is required to bring this technology to market, air conditioner manufacturers would be able to adopt this new technology without modifying their existing manufacturing tooling.

Recommendations

The results of this project indicate that significant energy demand reductions can be accomplished in the relatively near term if the tested technology is deployed in California. Because of the limited funds in the grant, the researcher only tested the control system on two air conditioning compressor units. To further this technology, additional testing is needed to assess the energy savings on a full range of commercially available air conditioning units. Research is also needed to fully define the distribution of motor quality to enable a more accurate projection of average efficiency improvement. Finally, the researcher should select a major manufacturer of air-conditioners as a partner in any additional research to insure that the technology development meets all market needs. The manufacturer will have to assess the impact of substituting three-phase motors for the present single-phase motors in the production of their sealed compressor units.

Public Benefits to California.

The primary benefit to California will be the availability of higher efficiency (8-10%) air conditioners to electric consumers that are limited to single-phase power. A second major benefit is the reduction in peak loading of the electrical system on hot summer days. Many advantages accrue to the ratepayers from the reduction in peak loads. The relatively near term availability of these benefits is due to the simple, modular nature of the control circuitry, which can be a simple add-on at first, with integration in depth developed as cost cutting measures by the manufacturers.

Stages and Gates Methodology

The California Energy Commission utilizes a stages and gates methodology for assessing a project's level of development and for making project management decisions. For research and development projects to be successful they need to address several key activities in a coordinated fashion as they progress through the various stages of development. The activities of the stages and gates process are typically tailored to fit a specific industry and in the case of PIER the activities were tailored to be appropriate for a publicly funded energy research and development program. In total there are seven types of activities that are tracked across eight stages of development as represented in the matrix below.

Development Stage/Activity Matrix

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Activity 1								
Activity 2								
Activity 3								
Activity 4								
Activity 5								
Activity 6								
Activity 7								

A description the PIER Stages and Gates approach may be found under "Active Award Document Resources" at: http://www.energy.ca.gov/research/innovations and are summarized here.

As the matrix implies, as a project progresses through the stages of development, the work activities associated with each stage needs to be advanced in a coordinated fashion. The EISG program primarily targets projects that seek to complete Stage 3 activities with the highest priority given to establishing technical feasibility. Shaded cells in the matrix above require no activity, assuming prior stage activity has been completed. The development stages and development activities are identified below.

Development Stages:	Development Activities:
Stage 1: Idea Generation & Work Statement Development	Activity 1: Marketing / Connection to Market
Stage 2: Technical and Market Analysis	Activity 2: Engineering / Technical
Stage 3: Research & Bench Scale Testing	Activity 3: Legal / Contractual
Stage 4: Technology Development and Field Experiments	Activity 4: Environmental, Safety, and Other Risk Assessments / Quality Plans
Stage 5: Product Development and Field Testing	Activity 5: Strategic Planning / PIER Fit - Critical Path Analysis
Stage 6: Demonstration and Full-Scale Testing	Activity 6: Production Readiness / Commercialization
Stage 7: Market Transformation	Activity 7: Public Benefits / Cost
Stage 8: Commercialization	

Independent Assessment

For the research under evaluation, the Program Administrator assessed the level of development for each activity tracked by the Stages and Gates methodology. This assessment is summarized in the Development Assessment Matrix below. Shaded bars are used to represent the assessed level of development for each activity as related to the development stages. Our assessment is based entirely on the information provided in the course of this project, and the final report. Hence it is only accurate to the extent that all current and past work related to the development activities are reported.

Development Assessment Matrix

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

The Program Administrator's assessment was based on the following supporting details:

Marketing/Connection to the Market. The market for this technology is the air conditioner manufacturer. The user market for a product with this technology is new air-conditioner installations. The potential U.S. market size is 7.5 million units annually. This market grows at a rate in excess of 10% per year. The researcher has not yet found a manufacturing partner to take the control system to market. No market studies have been done to test consumer acceptance of this innovation. No "should cost" estimates of this technology are available at this time. It is possible that some of the additional cost of the controls could be balanced by inventory cost reduction from using the same motor in all same-sized units produced.

Engineering/Technical. The feasibility of the control system has been proven for air conditioners in the 42,000 to 48,000 BTU/Hour range. The functional requirements for higher efficiency have been exceeded. Integration into a commercial product will take additional engineering development. No scientific breakthroughs appear to be required. Significant field testing under varying conditions will be required before a manufacturer will commit to production.

Legal/Contractual. Dr. Smith holds all patents. No legal or contractual issues have come to the attention of the Program Administrator. There is no agreement with a manufacturer to take the technology to market.

Environmental, Safety, Risk Assessments/ Quality Plans. The researcher must prepare quality plans including test procedures. The researcher must also prepare environmental, safety and risk assessment for the proposed product with the advanced controls. The Program Administrator knows of no problems that might surface as a result of preparing those plans. It is probable that the new control system would have to be certified by a group such as Underwriters Laboratory.

Strategic. This product has no known critical dependencies on other projects under development by PIER or elsewhere

Production Readiness/Commercialization. There have been no disclosures of the project results to potential manufacturers. There is no production readiness plan and no "should cost" estimates.

Public Benefits. Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary public benefit offered by the proposed technology is to make electrical energy more affordable in California. This will be accomplished by increasing the efficiency of air conditioner units that are limited to single-phase power. The increased efficiency will reduce usage and the ratepayer's electric bill. A conservative lifecycle cost analysis was performed using the following assumptions:

The researcher estimates a 5% penetration of the new air-conditioner market in the first year of availability, increasing an additional 5% per each year. If one assumes that a consumer operates a 48,000 BTU/Hr air conditioner selling for $ 4,200 retail for 2,000 hours per year, then the customer will save 1,057 Kwhr of electricity worth over $100 per year based on $0.10 Kwhr electricity costs. Based on a conservative estimate that the first cost of the AC unit was 5% higher or $210, the consumer would have a simple payback of 2.1 years. (The researcher must conduct significant cost studies to verify the estimated impact on first cost.) The public receives the benefits of reduced air pollution and more reliable power supply and quality, compared to the "business-as-usual" scenario using conventional single-phase air conditioners. The Program Administrator estimates that benefits from this project could be realized in less than five years.

Program Administrator Assessment:

After taking into consideration: (a) research findings in the grant project, (b) overall development status as determined by stages and gates and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow-on funding within the PIER program.

Receiving follow on funding ultimately depends upon: (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation and (c) successful evaluation of the proposal.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)

Appendix C: New Product Cost Estimates